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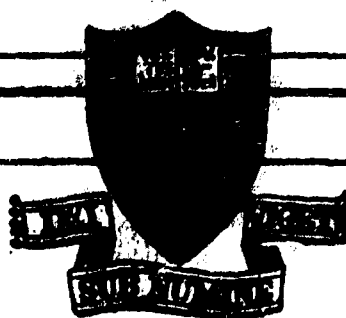
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PRINCETON UNIVERSITY
DEPARTMENT OF AERONAUTICAL ENGINEERING

U.S. Army Transportation Research Command
Fort Eustis, Virginia

Project Number: 9-38-01-000, TK 902
Contract Number: DA 44-177-TC-524

AN INVESTIGATION OF
ELECTRICAL CHARGING AND DISCHARGING
OF AIRCRAFT IN FLIGHT

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Report No. 593

December 1961

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ACKNOWLEDGEMENTS

The authors wish to acknowledge the excellent cooperation and assistance given by the personnel of the following: The U.S. Army Transportation Research Command, Fort Eustis, Virginia; The Cornell Aeronautical Laboratory, Buffalo, New York; and The Kellett Aircraft Corporation, Willow Grove, Pennsylvania.

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SUMMARY

A short theoretical investigation is made of the factors involved in the charging and discharging process of an airborne helicopter.

The dominant factor in keeping this charge small is a short discharge time constant compared with the charging time constant.

Practically, the only means of controlling the discharge time constant is by controlling the resistivity of the air.

Possible methods are discussed and evaluated. It is concluded that only corona discharge systems seem to be feasible at this time. Three possible corona discharge methods are discussed.

Active DC corona point, including a measurement device and sensing element mounted on the ship. (Ref. 8)

Active corona system with 2 DC corona points of opposite polarity mounted on the rotor blades, not requiring measuring and sensing elements.

Active corona system with AC corona point having a low frequency (400 cycles per second) AC voltage mounted on the rotor blades, not requiring measuring and sensing elements.

STATEMENT OF THE PROBLEM

The static charging of a helicopter in flight is important since it influences the safety of personnel and cargo. The discharging current may produce ignition and detonation of flammable materials, being therefore a great hazard to crew, passengers and cargo.

The Instrumentation and Control Laboratory has conducted a short theoretical study of the charging and discharging problems of a helicopter in flight, together with some simple laboratory experiments. This has been directed toward the investigation of the feasible methods of passive and active discharging methods.

DISCUSSION

A. The hazards of a charged aircraft.

An aircraft is considered to be charged if it has a potential with respect to the earth. When a charged aircraft comes into contact with a conductor of a different potential, the potential equalizes and hazards may occur, due to the equalizing current flow. Examples of these hazards are:

An electric shock to the personnel. Several safety criteria have been developed (Ref. 2, 8), but only a limited amount of data on hazards to personnel is available. It may be concluded that a capacitor charged with an energy of one joule discharging through a human body is lethal, and a capacitor charged with an energy of one millijoule is generally harmless. When the energy level reaches 0.5 millijoules, 500 μF , 1400 V, a discharge is noted. A discharge of one millijoule, 500 μF , 2000 V, gives a slight shock in the fingers. A discharge of 1.5 millijoules, 500 μF , 2500 V, gives a noticeable electrical shock which is felt in the hands.

Ignition of flammable gas mixtures. It has been reported that a spark with an energy of one millijoule is considered "plausible minimum ignition energy." (Ref. 4, 5).

Ignition of explosives. No accurate data are available on the investigation of the necessary ignition energy of military explosives. However, the following may be taken as a guide. Commercially manufactured explosives may be divided into two classes:

Initiators which require an ignition energy of from 10^{-6} to 10^{-2} joules.

Secondary explosives which require an ignition energy of the order of several joules. (Ref. 13).

B. Properties of the atmosphere related to the charging of aircraft.

After considering the properties of the atmosphere which are involved in the charging and discharging process of a helicopter in flight, a theoretical evaluation can be made of the factors which determine the stored energy on a helicopter.

Atmospheric conductivity of the lower atmosphere. (Ref. 6, 7, 9, 23)

The conductivity of the air is proportional to the concentration of charge carriers (electrons whether or not attached to molecules and ions), the charge of the charge carriers and the mobility of the charge carriers. In general, with increased height, the concentration of the charge carriers increases, due to higher cosmic ray intensity. The mobility of the charge carriers varies inversely proportional to the air density. The ions attach themselves to impurities, thereby forming "large ions" with reduced mobility. In the lower atmosphere the mobility and ion concentration depends upon the purity of the air. This explains the large variations in measured air conductivity. Figure 1 gives air conductivity versus height. The air resistance equals $\frac{1}{\text{air conductivity}}$. At sea level the still air resistance is in the order of $0.2 - 1 \times 10^{14}$ ohms per meter. The electrical conductivity of the air in the vicinity of a propeller or rotor system is increased over that of still air because the propeller or rotor system imparts a velocity to the air, and the effective mobility of the ions is increased. Since the resistivity of the air is a function of both the number of ions in the air and their mobility, the effect of this velocity is to reduce the resistivity. For example, in Reference 8 a resistivity of 0.1×10^{14} ohms per meter is used as a typical value in the vicinity of rotor air flow.

Electric fields in the lower atmosphere. (Ref. 6, 7, 9)

The electric fields in the atmosphere are caused by potentials in the atmosphere. In fair weather, at a height of 100 km, this potential is of the order of 400,000 volts positive with respect to the earth. In disturbed weather, this potential is negative and at the altitude of the thundercloud. The resistivity of the air at various heights determines the potential field strengths. Field strength (volts per meter) is equal to air resistivity (ohms per meter) times vertical electric current (amperes).

Fair weather field strength.

Figure 2 gives some measured values of fair weather field strength. At the earth's surface the fair weather field strength shows a large variation because of large variations in air resistivity. It should be noted that, although there may be relatively large changes in air electrical resistivity in the lower atmosphere causing wide variations in local potential gradient, the total fair weather electrical resistance and potential at high altitudes remain relatively constant, causing a relatively constant total fair weather vertical current. The present explanation for these vertical air currents is that there are continuously active thunderstorms somewhere over the earth. These storms give an upward current of the order of 2,000 amperes. This is the supply current that keeps the ionosphere charged to 400,000 volts positive with respect to the earth. This positive potential, together with a more or less total constant air resistance between earth and ionosphere, produces the fair weather downward air current.

A typical average value is in the order of 130 volts per meter.
 Typical fair weather potentials of the lower atmosphere are given in the following Table.

<u>Height</u> <u>(feet)</u>	<u>Fair Weather</u>	<u>Potentials in Volts</u>
	<u>Order of Magnitude</u>	<u>Typical Average</u>
10	150 - 900	400
20	300 - 1800	800
30	450 - 2700	1200
40	600 - 3600	1600
50	750 - 4500	2000
60	900 - 5400	2400

Disturbed weather field strength.

The disturbed weather field strength depends upon the charge of the thundercloud and its position under the charged cloud. Typical values at ground level are 500 volts per meter, positive or negative depending upon the ground position relative to the charged cloud. Some of the measured magnitudes of the electric field in disturbed weather are as follows: (Ref.9).
 Average vertical field within nonprecipitating clouds < 1000 volts per meter.
 Average vertical field within stable precipitating clouds < 4000 volts per meter.
 Average maximum vertical field observed in nine different thunderclouds

130 K volts per meter.

Maximum field observed just prior to lightning striking an aircraft

340 K volts per meter.

C. The basic mechanisms for generating static electricity. (Ref. 11, 15)

Static electricity is caused by various means.

Frictional electricity. (Ref. 11) When two dry materials with different dielectric constants (nonmetals) come into contact with each other and then separate, the material with the highest dielectric constant will be charged positively. (Law of Coehn). For example, a rod of glass and a piece of silk. It is believed that electrification is a result of the exchange of molecular ions. This phenomenon is very complicated since changes in the structure of the surface, such as in a film of oil, have great effects on the generated voltages.

Spray electricity. (Ref. 11) The disruption of surface liquid films by mechanical forces causes the electrical double layer to break (for example: water outside negative, inside positive). This results in the separate parts having dissimilar charges and hence causes static charging.

Electrolytic electricity. (Ref. 11) This is caused by a distribution of electrolytic ions in solutions of liquids of high dielectric constant between the solutions and the metal or solids. This diffusion of ions can build up large potentials. If a mechanical separation follows, a large electrostatic voltage may develop (for example, oil).

Contact or voltaelectricity. When two clean surfaces of metals or semiconductors come into contact with each other, the metal with the higher work function will become positive because more electrons diffuse from that metal to the metal of the lower work function. The resulting voltages are small.

Ions and electrons. Ionization can be caused by inelastic collisions, heat or radiation. A more detailed discussion of the formation of ions and electrons is given later in this report.

D. Static electrical properties of a helicopter in the atmosphere.

The capacitance of a helicopter with respect to earth, assumed as a perfect conductor in an infinite atmosphere, depends only on its shape and dimensions. The capacitance of some shapes in free air are given:

Capacitance of a sphere: $C = 4\pi\epsilon\sqrt{\frac{S}{4\pi}}$

Capacitance of a spheroid: $C = \frac{8\pi\epsilon\sqrt{b^2 - a^2}}{\ln \frac{b + \sqrt{b^2 - a^2}}{b - \sqrt{b^2 - a^2}}}$

Where C is the capacitance, farads

R is the radius, meters

$4\pi\epsilon$ is the constant $\frac{1}{9 \times 10^9}$

a is half the short axis of the spheroid, meters

b is half the long axis of the spheroid, meters

S is the surface area, meters²

A simplified shape of the helicopter is assumed, and various capacitances for that assumed shape can be calculated. (Ref. 10, 8)

<u>Dimensions</u>	<u>Capacity - Sphere ($C = 4\pi\epsilon R$; $R = l/6$)</u>	<u>Capacity - Spheroid</u>
H37 (Sikorsky)	460 μ F	650 μ F
Length = l = 25m		
Diameter = d = 6m		
H21 (Vertol)	490 μ F	570 μ F
Length = l = 26.2m		
Diameter = d = 4.3m		
H40 (Bell)	220 μ F	380 μ F
Length = l = 12m		
Diameter = d = 4.4m		

As seen by the above Table, a sphere having a diameter of one-third the longest radius of a helicopter, approximates the capacitance of that helicopter. Due to the relatively simple configuration of a sphere in the calculations, a spherical model is further used in the following calculations. The capacitance of a helicopter approaching earth is equal to the sum of the capacitance of a helicopter in infinite atmosphere and the capacitance of the helicopter to the earth. The latter depends mainly upon the surface of the aircraft facing the earth and the height of the aircraft above the earth. At normal hover heights this added capacitance is small compared with the capacitance of the helicopter in free air, and therefore will be ignored.

The effective electrical resistance of a helicopter, assumed as a perfect conductor in an infinite atmosphere, depends upon its shape and dimensions, as well as upon the resistivity of the air. The capacitance is also a function of the shape and dimensions of the helicopter. The effective resistance can be expressed in terms of the capacitance of the helicopter, and is equal to: $R_{\text{eff}} = 8.8 \times 10^{-12} \frac{\rho}{C}$

where: R_{eff} is the effective resistance from the helicopter to the atmosphere.

ρ is the resistivity of the air in ohms per meter.

C is the free space capacitance of the helicopter.

The effective resistance of a helicopter approaching earth is equal to the parallel combination of the effective resistance towards an infinite atmosphere and the effective resistance between the aircraft and the earth. The latter depends mainly upon the surface of the aircraft facing the earth and the height of the aircraft above the earth.

Assume that a helicopter is flying in an infinite atmosphere. The helicopter will charge itself towards the potential of the atmosphere with a time constant, T_c . $T_c = R_{eff} \times C = 8.8 \times 10^{-12} \frac{\rho}{C} \times C = 8.8 \times 10^{-12} \rho$ which is independent of helicopter dimensions. In still air, assuming a conductivity in the order of 3×10^{-14} mho per meter or a resistivity of 3×10^{13} ohms per meter, the time constant is in the order of 270 seconds. This time constant depends only on the resistivity of the atmosphere. When the helicopter has a higher potential than the surrounding air, the helicopter discharges to the potential of the surrounding air with that same time constant. When a helicopter becomes charged because of one or more of the basic mechanisms for generating static electricity, the discharge of the helicopter will take place through the resistance of the air. The final value to which the helicopter will be charged then, depends on the time constant of the discharging process. If the time constant is short, the helicopter will be unable to attain a potential which differs from that of the surrounding atmosphere. If the time constant is long, the helicopter will be charged to a high potential compared to that of the surrounding atmosphere. Thus we see that the charging and discharging time constant is a key to determining the ship's potential. We have noted that the time constant, for all practical purposes, is independent of the dimensions of the ship and is only a function of the resistivity of the air. Therefore, the resistivity of the air must be changed to change the potential of the ship. The basis for all discharge systems is the lowering of the resistivity of the air.

E. The charging and discharging process of a helicopter in flight.

When the processes described below increase or decrease the absolute potential of the helicopter with respect to the earth's potential, the process is called a charging or discharging process. The main processes are as follows:

Atmospheric charging processes. A helicopter flying in the atmosphere, with all other charging processes absent, will be charged or discharged to the atmospheric potential that exists at the height at which the helicopter is flying, as has been previously indicated. The time constant will be approximately one to two minutes.

Precipitation charging processes. When particles are striking an aircraft in the atmosphere, a precipitation charge may develop due to one, or a combination, of the following basic mechanisms.

Frictional electricity

Spray electricity

Electrolytic electricity

Contact or voltaelectricity

With measurements from different sources (Ref. 4, 9, 21) the charge rates due to precipitation for an aircraft of $200\mu\text{F}$, are calculated in the following Table.

	<u>Charge developed on an Aircraft $C = 200\mu\text{F}$</u>
Quiet rain	+ 0.3 to - 0.5 KV/sec.
Shower rain	+ 10 to - 10 KV/sec.
Electrical storm rain	+ 21 to - 13 KV/sec.
Quiet snowfall	+ 0.1 to - 0.1 KV/sec.
Squall snowfall	+ 1.5 to - 0.8 KV/sec.
Dust	+ 5 to + 13 KV/sec.
Fuel drops	- 4 to - 38 KV/sec.

The charge rate at which the aircraft is charged, with no discharge mechanisms present, depends on the material, mass and charge intercepted. The amount of charge present on the aircraft is a function of the total amount of precipitation intercepted. Hence the bigger the aircraft, or larger the area, and/or the higher the speed, the larger the amount of charge collected by the aircraft in flight.

The self-generating charging process. The main source reported for the self-generating charging process is the combustion engine, which gives ions of one predominant polarity. Also, the ion generation is probably a function of fuel and air composition, as well as engine condition. The aircraft is charged to the opposite polarity of the ions. The order of magnitude reported is of the order of several kilovolts negative. (Ref. 8).

Corona discharging process. The basic mechanism of a corona consists of electrons which are accelerated by the strong electric field around the "sharp" point. The field strength around the sharp point is directly proportional to the potential, and inversely proportional to the radius of curvature of the point. Thus, when the radius needs to be very small (sharp point) the field strength can be quite large. The accelerated electrons ionize the air by producing an avalanche. The ions (space charge) are removed from the point by the motion of the air or by the electrical potential field.

The DC discharge current from a corona point in still air, with no other charges present, is given by:

$$i = cV(V - V_c)$$

where i is the discharge current in amperes

c is the constant, depending on the mobility of ions (order of magnitude 2×10^{-4} m/sec per volt, the permissivity of empty space ($\epsilon = 8.8 \times 10^{-12}$ farad/meter), the particular gas present, the diameter of the point, and the air gap.

V_c is the voltage at which the corona current starts. This voltage depends on the atmospheric condition and the dimensions of the corona point.

V is the voltage at the corona point with respect to the air immediately around the corona point.

If no other electrical fields are present, this voltage is equal to the voltage impressed on the corona point. If other electrical fields are present, this voltage is equal to the voltage with respect to a reference point, impressed on the corona point, increased or decreased with a voltage of the order of the potential difference of the field between the corona point and the reference point. A discharge current in the order of tenths of a microampere occurs if the voltage on the point exceeds a certain predetermined value V_c . One of the most important points concerning corona discharge, is that the corona discharge current is space charge limited. The method of increasing the corona current consists of removing the space charge (ions) by:

Larger voltages on the corona point (or increased field strength so that the ions will have large speed).

"Blowing" away the space charge which results in faster traveling ions.

A more detailed discussion of this subject is given elsewhere in this report.

F. The charge of a helicopter in flight.

Assume an uncharged airborne helicopter that becomes charged because of one or more of the charging processes, as discussed in the preceding pages. As the potential of the helicopter rises above the potential of the surrounding air, the helicopter starts discharging towards the atmosphere, with a time constant in the order of 90 seconds. This discharge time constant is normally very long compared with the charge rates of the precipitating and self-generating charging processes (few seconds). The potential of the helicopter rises to a potential of:

$$V = \frac{Q}{C}$$

where V is the voltage in volts

Q is the net charge in coulombs

C is the capacitance of the aircraft in farads.

When the potential rises, the corona discharge process comes into effect. This is mainly corona current from sharp points. The potential of the helicopter rises to such a voltage that the total outgoing corona current equals the incoming charging current.

Effect of helicopter size. In comparing a large and a small helicopter, assumed to be the same shape and flying at the same speed under the same conditions, the charging and discharging effects are:

Atmospheric charging process: Both helicopters are charged to the same potential.

Precipitation charging process: The larger helicopter intercepts more charge than the smaller one, hence accumulates more charge.

Self-generating charging process: The larger helicopter intercepts more charge. However, this need not be in the same ratio as differences in surfaces, because of aerodynamic effects.

Corona discharging process: The amount of current discharge is a function of (the voltage)². Since the incoming charge or current is larger in the larger helicopter, the outgoing current must be larger (or equal to the incoming current). Since the outgoing current is mainly a corona current, the potential of the larger helicopter must be larger than the smaller helicopter. Some particular potentials of the charged helicopters have been reported to be as high as 20 to 50 KV. (Ref. 8).

G. The requirements for diminishing the hazards of a charged helicopter.

The static electric energy of a charged helicopter is:

$$W = 1/2 CV^2$$

where W is the energy in joules

C is the capacitance of the helicopter in farads

V is the voltage of the helicopter in volts.

Figure 3 is a graph of the stored energy as a function of capacitance and voltage.

We have indicated that a static energy of less than one millijoule with respect to earth is permissible. In order to bring and/or keep the static energy of the helicopter to less than one millijoule, a "discharger" is needed. Where dischargers are needed, the potential of the helicopter is compared with the potential of the surrounding atmosphere. (This is done automatically by the "passive" dischargers, or measured in the case of controlled dischargers). When a discharger is able to discharge a

helicopter to zero potential, this means the zero potential with respect to the surrounding air and not zero potential with respect to the ground. Thus, if a discharging scheme is working properly, it will bring the potential of the helicopter to the potential of the surrounding air which is not at earth's potential. Therefore the helicopter will retain an unknown voltage with respect to the earth. The polarity and magnitude depend upon the atmospheric condition. For example, in fair weather, the unknown voltage is in the order of 130 volts per meter of height (+ 100% error) near sea level.

The assumption of a height of 25 feet (8.3 meters) corresponds in fair weather to a potential of the order of 1250 volts. The larger helicopters may have a capacitance up to 1000 μF . Hence a potential of 1250 volts on 1000 μF corresponds to:

$$W = 1/2 \times 10^3 \times 10^{-12} \times (1.2 \times 10^3)^2 = 0.8 \text{ millijoules.}$$

However, a potential of 2500 volts on 1000 F corresponds to:

$$W = 1/2 \times 10^{-9} \times (2.5 \times 10^3)^2 = 3.1 \text{ millijoules.}$$

We have previously indicated that a discharge up to one millijoule is quite reasonable and safe. However, for the larger helicopter, this is not always obtainable because of the atmospheric potentials which might exist. Even if the potential between the helicopter and the surrounding air remains zero, higher energy levels than one millijoule may occur. We can see, therefore, that since discharge systems tend to discharge the helicopter to zero potential with respect to the surrounding atmosphere, it is possible that a large "discharged" helicopter may still possess several millijoules of electric energy. A discharge system which keeps the helicopter within the order of one millijoule energy with respect to the surrounding atmosphere, seems to be a reasonable compromise.

H. Discussion of a possible solution.

There are three possible approaches in preventing the helicopter from being charged to a high static voltage. These approaches are:

Preventing the helicopter from acquiring a charge by eliminating the charging mechanisms in whatever environment the helicopter is flying.

When elimination of the charging mechanisms is not feasible, a discharge method has to be applied, in order to maintain the helicopter at a low static voltage with respect to the earth.

Preventing the discharge at the loading or handling point (for example, isolated hook).

Preventing the helicopter from acquiring a charge. Let us consider the ideal case where only one specified charging mechanism is present. Theoretically, a suitable coating can be provided to accommodate this condition, causing no charge to be developed. If this specific charging mechanism is, for example, frictional electricity, we know that the material with the highest dielectric constant will be charged positively. If the materials have the same dielectric constant, no charge develops. It is apparent that a coating can be developed for a specific case of frictional electricity if the materials are known. However, in practice, there are many different frictional electricity generating materials possible, each requiring a different coating for the different varieties of precipitation. Thus, even in a simple case, a practical solution involving the use of a passive coating is not readily discernible. Since there are several other basic charging mechanisms, each with a wide variety of environments, the problem becomes more complex. Several mechanisms are usually present, each requiring different passive coatings at different times.

The self-generating charging process. As far as the authors know, there is no practical process available for preventing a charge on the helicopter by controlling the self-generating charging mechanisms.

In conclusion then, all charging mechanisms of precipitating and self-generated charging processes which generate build-up charges must be eliminated at the same time, by the same coating, to prevent a helicopter from becoming charged. This is an impossible process. Therefore, a practical solution involving the use of passive coating is not readily discernible, and further investigations do not seem practical.

Discharging by ionization. The chief particles which might be used for ionization are electrons, ions or photons.

Ionization by electron collision. A high energy electron, traveling with a high velocity, ionizes the air and loses energy in the inelastic collisions with the atoms. Electron energy is expressed in electron volts. Energy necessary for ionization is also expressed in electron volts. A method of estimating the ionization caused by high velocity electrons, is to determine the number of ion pairs produced when the electron loses its energy along its path in air. This average ionization energy is obtained by dividing the initial electron energy by the number of ion pairs formed per electron. This is a function of the initial electron energy. (Ref.12, 24). If the initial electron energy is between 500 and 1000 electron volts, the average energy needed to produce an ion pair is approximately 45 electron volts. If the electron energy is larger than 4000 electron volts, the average energy needed to produce an ion pair is approximately 33 volts. For example, one electron of a β ray of 17 kev electrons produces in the order of $\frac{17 \times 10^3}{33} \approx 520$ ion pairs.

Methods for producing high energy electrons are: β rays from a radio source and electron guns.

Ion collision ionization. A high energy ion traveling with a high velocity ionizes the air and loses energy in those inelastic collisions with other atoms. Since the mass of the ion is much larger than the mass of an electron, the energy lost by an ion in a collision is larger than the energy lost by an electron in a collision. Hence it is probably that the average energy needed to produce an ion pair by an ion collision is somewhat larger than that needed for an electron collision. The larger the ion, the larger the average energy necessary for ionization. Also, the average ionization energy is a function of the initial ion energy. (Ref. 12, 24).

Methods for producing high energy ions are radioactive sources and ion guns.

Photon ionization. When the energy of a photon is greater than the ionization energy of the atom, ionization may occur. However, there exists an optimum energy of the photon for which the probability of ionization is maximum. (Ref. 12). If n_0 is the number of photons entering the gas, the energy for each photon is $h\nu$, so the available energy is $W_0 = n_0 h\nu$ or $n_0 = \frac{W_0}{h\nu}$, where h is Planck's constant = 6.624×10^{-34} joules per second.

ν is the frequency in cycles per second.

Methods for producing photon ionization are ultra violet light (energy too small for practical discharge use), X rays, and Gamma rays from a radioactive source.

General discussion of ionization by particle radiation. The principle of operation of ionization by particle radiation, is to ionize the air around the ionizers, thereby reducing the resistivity of the air in the vicinity of the ionizers which, as has been previously shown, results in a reduction of the time constant of the helicopter. Unfortunately, ionization to eliminate a static charge can also produce physiological effects. The limit for the rate of ionization in any unrestricted area is a radiation level of no more than 2 milliroentgens per hour. (Ref. 21). This corresponds to 0.56×10^{-6} esu of current per cubic centimeter. The effect of this physiological limit on the maximum amount of current per cubic centimeter which is permissible, is that a very large volume of air must be ionized. For example, one could calculate an approximate volume of air which would have to be ionized as follows: If we assume that the average current of the helicopter in flight is of the order of 10 microamperes (which is a reasonable value), and if we assume that the ions which are created by the radiation are completely utilized in discharging the helicopter, we discover that a volume of $5.4 \times 10^4 \text{ m}^3$ would have to be irradiated by particles. This, of course, is an unreasonable and impractical volume. This means, in practice, that whatever rays are used to produce ionization, a considerable space will have to be irradiated at a rate much higher than the previously mentioned limit, and special shielding measures must be taken. No "safe" radioactive paint or radioactive discharger exists which does not exceed the limits set for an unrestricted area.

To have a radioactive source with minimum hazards and shielding, the source must have only β radiation of a low energy, since this type of radiation is easily absorbed. For example, the properties of tritium are: half life 12.5 years; β radiation; 18 kev; activity one curie per square inch;

ion current 10^{-7} amperes per square inch. By extrapolating, a source in the order of 100 curies is needed for a 10 microampere current. The radiation level can be estimated as follows:

$$\beta \text{ flux} = \frac{(\text{number of disintegrations/curie/sec.})(\text{number of curies})}{\text{surface area}}$$

For example, at the surface of the source, one can calculate the electrons per second per square centimeter:

$$N = \frac{(3.7 \times 10^{10}) \times 10^2}{6.25 \times 10^2} = 0.59 \times 10^{10} \text{ electrons per second per square centimeter}$$

$$\begin{aligned} \text{The radiation level} &= \frac{N \times \text{electron energy} \times \text{charge electrons}}{\text{energy required to form an ion pair}} \\ &= \frac{(0.59 \times 10^{10}) \times 18 \times 10^3 \times (4.8 \times 10^{-10})}{32.5} \\ &= 1.57 \times 10^3 \text{ roentgens per second} \\ &= 1.57 \times 10^3 \times 60 \times 60 \times 10^3 \\ &= 5.6 \times 10^9 \text{ milliroentgens per hour} \end{aligned}$$

The problem is relieved by interposing distance between the source and personnel connected with the operation of the aircraft. β radiation is absorbed by the air directly proportional to the product of density and distance between the source and the observer. Statistical calculations can be made to determine the range. The range is determined as the point where the extension of the linear portion of the curve meets the background radiation. Different investigators assume different constants and, therefore, the range calculations differ according to different linearizations. The range is in the order of 0.5 - 1 centimeter. However, at this range there exists a radiation of a few percent of the maximum radiation, which, with this large source of 100 curies, is still in the order of 10 million times the limit of 2 milliroentgens per hour. These figures show that

shielding is necessary. Shielding materials are available (Ref. 24) and are possible. Although this radiation level decreases with the distance from the source and shielding, the hazards of such a large source of 100 curies in handling and storage, possible contamination of an air field, and possible accidents, make the radioactive source very unattractive.

The above discussion indicates that particle ionizers are not the right approach to the solution of static electricity, as the same effect which is necessary for discharging also produces harmful physiological effects, thus eliminating the possibility of "safe" radioactive coatings and paintings. However, radioactive sources could be used if all the problems of shielding, handling, storage, personnel safety and provision against possible contamination of air fields are accepted. Since the same result can be achieved by other means (corona dischargers) further investigation of dischargers with these principles does not seem worthwhile in an analytical study such as this, since the main problems concerned with their use are practical ones involving operational problems rather than an academic analysis. Note: Commercial available antistatic sprays and coatings investigated, provide a relatively low resistance path to the ground via the coating, and are hence not applicable to the present problem.

Thermal ionization dischargers. Ionization occurs in high temperature flames and high pressure arcs. In the literature various kinds of ionizers, working on this principle, have been described (Ref. 19). Also the aircraft engine could be used as an ion generator (Ref. 8). The basic problem in the use of thermal ionization dischargers is that the generation of ions by thermal methods is an inherently inefficient process. For example, in a high

temperature flame, such as that associated with a propulsion rocket, the number of ions created represents only a very small fraction of one percent of the atoms. Thus, in thermal ionizers a larger portion of the energy expended is not used in making ions. A second objection to this method of creating ions is that there is great difficulty in controlling the polarity and number of the ions generated.

Electrical field strength ionizers or corona systems. In the following discussion five different methods of creating ionization in corona systems will be discussed. These five methods are:

One corona point in still air.

One passive corona point on a charged sphere in still air.

One corona point in still air with AC and DC potentials,
no other charges present.

Two corona points in still air with opposite DC potentials,
no other charges present.

The influence of wind on corona points.

The corona current in still air is given by: (Ref. 12, 18)

$$i = k v (V - V_c)$$

where V is applied voltage at the point (volts)

V_c is the corona starting potential (volts)

c, k are constants

v is the velocity of the ions (meters per second)

The velocity of the ions is proportional to the applied voltage at the point and is equal to a constant times ion mobility times applied voltage, which makes the above equation become

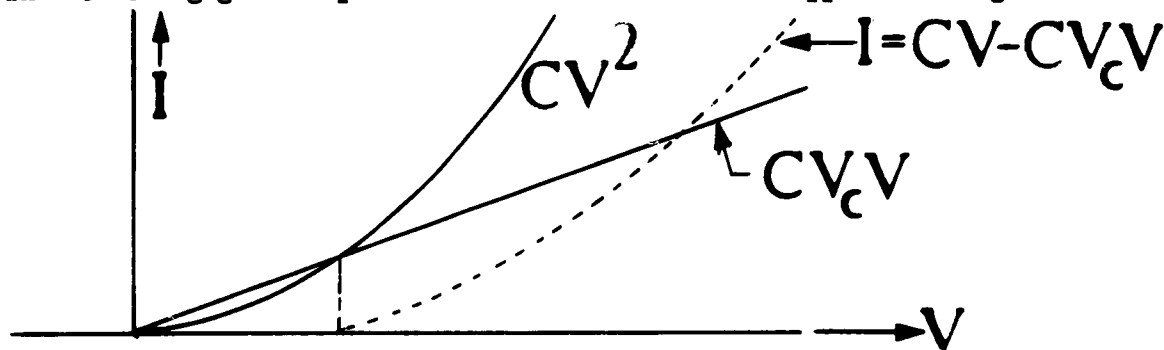
$$i = cV(V - V_c)$$

We assume the mobility of the positive and negative ions are both equal and in the order of 1.4×10^{-4} (m/sec/volts/cm). From the above equations it can be seen that methods for increasing the corona current are:

A change in potential at the point, V .

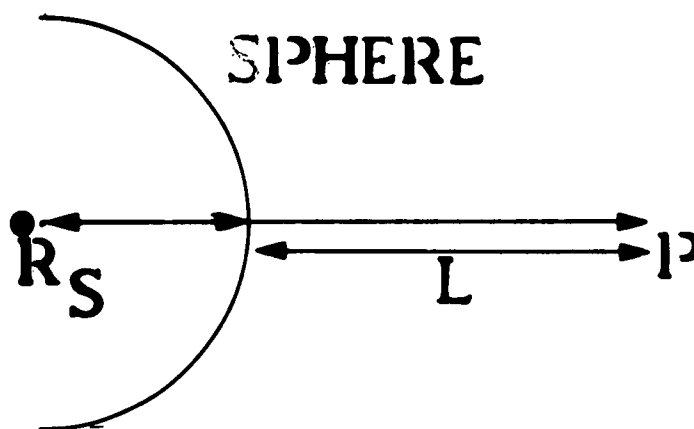
A change in the ion velocity, v .

The following gives a plot of corona current versus applied voltage.



It should be noted that two corona points give twice the corona current of one corona point, as long as the electrical fields of both points do not interfere (order of distance 30 - 50 cm for low point voltages).

Passive corona point on a charged sphere in still air.



The aircraft and the passive corona point are both at a potential V_s .

Assume that there is no corona point, then the potential V_p at a point P is:

$$V_p = \frac{1}{4\pi\epsilon} \frac{Q}{r_s + l} \quad (1)$$

if all charge Q is located at point O.

where l is the length of the corona point (meters)

r_s is the radius of the sphere (meters).

$$\frac{1}{4\pi\epsilon} = 9 \times 10^9 = \text{constant}$$

If the potential of the surface of the sphere is V_s , the same potential V_s

will exist on the surface if a charge Q_s is located at O or:

$$V_s = \frac{1}{4\pi\epsilon} \cdot \frac{Q_s}{r_s} \text{ or } Q_s = 4\pi\epsilon \cdot V_s \cdot r_s \quad (2)$$

Equation (2) is substituted in (1) and:

$$V_p = \frac{1}{4\pi\epsilon} \cdot \frac{4\pi\epsilon \cdot V_s \cdot r_s}{r_s + l} = V_s \cdot \frac{r_s}{r_s + l} \quad (3)$$

However, if a corona point P with length l is attached to the surface of the sphere, then the potential of the point is V_s . The potential difference between the corona point and the surrounding air is then always less and in the order of:

$$V_s - V_s \frac{r_s}{r_s + l} = V_s \frac{l}{r_s + l} = \frac{V_s}{r_s} \frac{l}{1 + l/r_s} \quad (4)$$

The field strength at the surface of the sphere is:

$$F = \frac{Q}{4\pi\epsilon r_s^2} \quad (5)$$

Equation (2) is substituted in (5):

$$F = \frac{4\pi\epsilon V_s r_s}{4\pi\epsilon r_s^2} = \frac{V_s}{r_s} \quad (6)$$

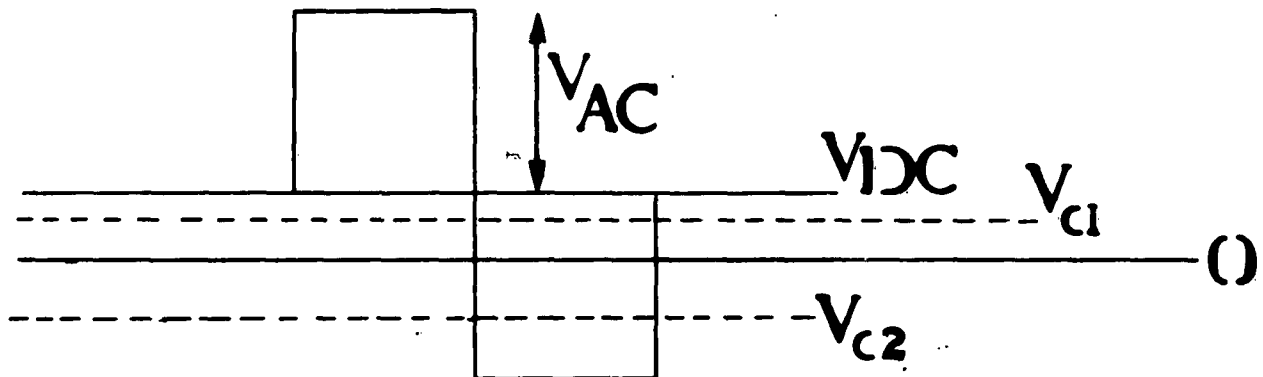
The use of a passive corona point has the following properties:

The potential of the corona point is always less than the length of the corona point times the field strength if the corona point is not present. (Eq. 4) The potential of the corona point increases as the length of the corona point increases.

There is a certain dead zone around zero in the order of several kilovolts, for the corona current starts when the potential exceeds a predetermined potential V_c (the latter depends upon the geometrical form of the point).

A passive corona point has the effect of preventing a helicopter from obtaining very high potentials because the corona currents increase as the potential increases.

Corona point in still air with AC and DC potentials, no other charges present.



where V_{c1} is the voltage at which the positive corona starts

V_{c2} is the voltage at which the negative corona starts

V_{AC} is the AC voltage square wave with respect to DC

V_{DC} is the DC potential of the point with respect to the air.

Discharge current at positive half cycle of AC square voltage

$$i_1 = C_1 [V_{AC} + V_{DC}] [(V_{AC} + V_{DC}) - V_{C_1}]$$

Discharge current at negative half cycle of AC square voltage

$$i_2 = C_2 [V_{AC} - V_{DC}] [(V_{AC} - V_{DC}) - V_{C_2}]$$

Assume $C_1 = C_2 =$ corona point constant.

The total net corona current per cycle is:

$$\frac{1}{2} C [2V_{AC}V_{DC} - V_{C_1}V_{DC} + 2V_{AC}V_{DC} - V_{C_2}V_{DC}]$$

In the case where $V_{C_1} = V_{C_2}$ the total discharge current is:

$$i = \frac{1}{2} C [4V_{AC}V_{DC} - 2V_{C_1}V_{DC}] = CV_{DC} [2V_{AC} - V_{C_1}]$$

If there is only DC on the corona point

$$i = CV_{DC} [V_{DC} - V_{C_1}]$$

In the equation, V_{AC} can be chosen so that $2V_{AC}$ is larger than V_{C_1} and has a fixed value and a dead zone does not exist. The corona current is only determined by V_{DC} and proportional to V_{DC} . But also by choosing V_{AC} larger than V_{DC} a larger discharge current can be obtained than in the case of a corona point with only DC voltages. For example if we take $V_{AC} = V_{DC}$ then the corona AC/DC corona point is more than twice the corona point of a DC corona point. In the case where the AC voltage is not a square wave, but a sinusoidal wave, a form factor is applied to the equation. For example, a form factor for a sine wave as compared to a square wave is .63. Hence the equation becomes:

The difference is positive and negative corona starting potential means that the negative and positive currents are slightly different than calculated. The mobility of positive and negative charge carriers is also different:

	<u>Positive mobility m/s/V/m</u>	<u>Negative mobility m/s/V/m</u>
dry air	1.4×10^{-4}	2.1×10^{-4}
very clean air	1.8×10^{-4}	2.5×10^{-4}
air	1.6×10^{-4}	2.2×10^{-4}

The difference in mobility of the ions has two effects:

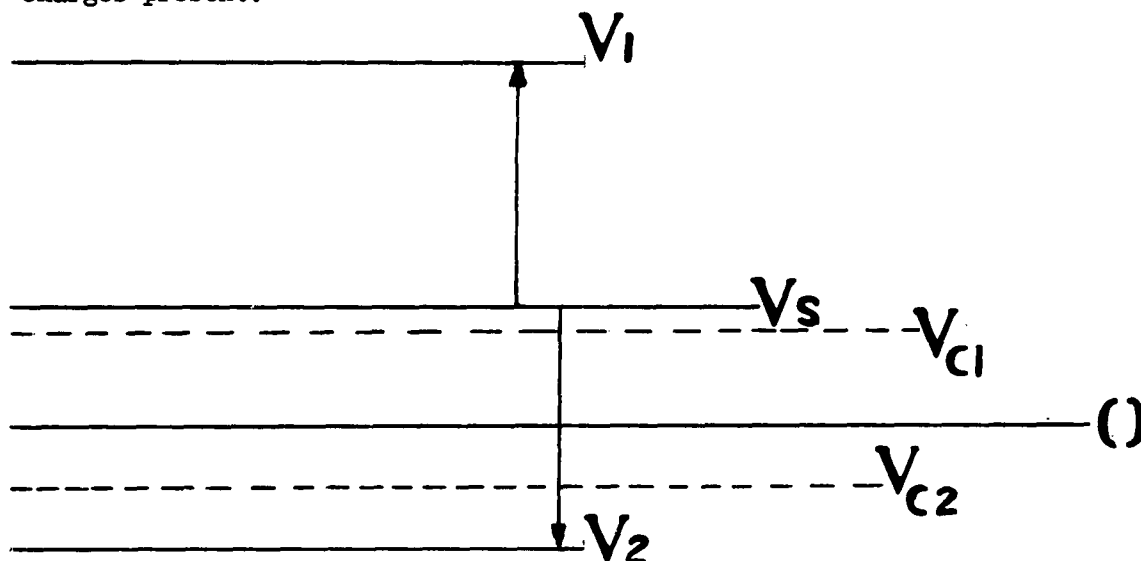
When no charging mechanism is present, the effect of a larger negative ion mobility charges the helicopter to a potential that neutralizes this effect. A wind of one m/s has the same effect as an effective potential in the order of 16 kilovolts. The ion mobility difference is in the order of 0.4×10^{-4} m/s/V/m, hence gives a zero shift of the null potential which in kilovolts is of the order of 0.06 times the applied effective voltage in kilovolts. The actual positive corona current will be smaller than the calculated current, while the negative corona current will be larger than the calculated corona current. This observation has been confirmed by laboratory tests.

The effect of AC frequency on the corona discharge (Ref. 12, 18).

Laboratory tests were made at 400 cycles per second. Tests were also made to investigate if low AC voltages in the frequency range of a normal VHF radio (100 m c/s range) had any special discharge effects. No discharge effects were noted as long as the DC voltage remained below the expected DC corona starting voltage. Above these voltages the corona currents remained as expected. Tests were made up to 15 kilovolts DC potential.

At low frequencies, the period is long compared with the transit time of ions and electrons in the main influenced field space around the corona point. When the frequency is increased, the transit time of the ions becomes significant. There is probably a slight decrease in the corona starting potential and a decrease in the net corona current output as the frequency is raised. It is expected that the above effect will occur in the region of 10 - 20 kilocycles per second.

Two corona points in still air, each with a DC potential. No other charges present.



where V_s is the DC voltage on the ship

V_{c1} is the voltage at which the positive corona starts

V_{c2} is the voltage at which the negative corona starts

V_1 is the DC voltage on the positive corona point

V_2 is the DC voltage on the negative corona point

Discharge current on the positive corona point

$$i_1 = C_1 [(V_s + V_1)(V_s + V_1) - V_{C_1}]$$

Discharge current on the negative corona point

$$i_2 = C_2 [(V_2 - V_s)(V_2 - V_s) - V_{C_2}]$$

Assume that $C = C_1 = C_2 =$ corona point constant

$$V = V_1 = V_2 = \text{DC voltage applied to the corona points}$$

The total net discharge current is

$$i_1 - i_2 = C [4V_s V - 2V_C V_s + VV_{C_2} - VV_{C_2}]$$

$$\text{Assume } V_{C_1} = V_{C_2} = V_C$$

$$\text{Then } i_1 - i_2 = C [4V_s V - 2V_C V_s] = 2CV_s [2V - V_C]$$

By comparing this current to the corona current from a DC point, it is noted that the corona current is four times larger than the corona current from a DC corona point, if V_s and V are both equal to V_{DC} . Also, this system has no "dead" zone. The assumption is that positive and negative ion mobility is equal and $V_{C_1} = V_{C_2}$.

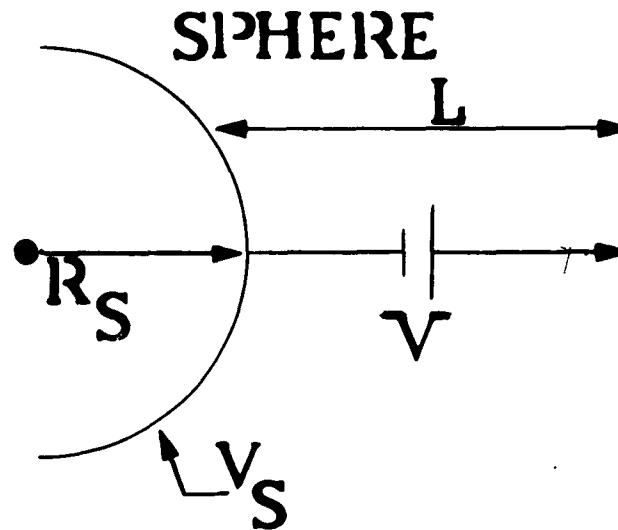
The difference in positive and negative ion mobilities has the following effects:

When no charging mechanisms are present and DC potentials are equal, there occurs a zero shift of the null potential which is in the order of 0.06 times the applied effective voltage in kilovolts. This can be compensated by using different DC voltages.

The actual positive/negative corona current will be in the order of 20% smaller/larger than the calculated current.

The difference in positive and negative corona starting potential also means that the actual currents may differ somewhat.

Active corona point on a charged sphere in still air.



Analogous reasoning as for the passive corona point, gives a potential at point P, due to the charged sphere of $V_P = V_S \cdot \frac{r_S}{r_S + l}$. The potential

of the isolated corona point is V increased with the potential of the sphere to the order of the effective potential of the corona point. The difference between the corona point potential and the air directly around it is:

$$V_{\text{eff}} = V + V_S - V_S \frac{r}{r_S + l} = V + V_S \left(\frac{l}{r_S + l} \right)$$

As is seen from the above equation, the effective potential of the corona point is increased if the sphere acquires a charge. The dischargers are intended to keep the sphere at zero potential with respect to the air, so it is assumed, also for simplicity, that the influence of the charge of the sphere is zero, in the following discussion. This is the most conservative assumption possible.

The influence of wind on corona points (Ref. 18)

Corona current with wind along the corona point.

$$\begin{aligned}\text{Corona current: } i &= k(v + w)(V - V_c) \\ &= kv\left(1 + \frac{w}{v}\right)(V - V_c) \\ &= kv(V - V_c)\left(1 + \frac{w}{v}\right)\end{aligned}$$

where V is the applied voltage at the corona point (volts)

V_c is the corona starting potential (volts)

k is the constant

v is the velocity of the ions (meters/second)

w is the wind velocity (meters/second)

The corona current with wind along the corona point is equal to the corona current in still air, multiplied by a factor $\left(1 + \frac{w}{v}\right)$ or $\left(1 + \frac{w}{k_1 b V}\right)$

Hence the wind influence can be summarized as follows. For an active or passive DC corona point, mounted on a charged or uncharged sphere, the derived results for still air remain valid and can be applied in the case where a wind is blowing along the corona point, if the result is multiplied by a factor $\left(1 + \frac{w}{k_1 b V}\right)$ or $\left(1 + \frac{w}{v}\right)$

where w is the wind (meters/second)

k_1 is the constant

b is the ion mobility (m/s/volts/m)

V is the potential of the point (volts) or effective voltage (volts).

The enormous influence of the wind can be seen in Fig. 4.

DC and AC corona points, or two DC corona points with opposite potentials have an influence as follows (same notation as for corona points with opposite potentials).

Assume $V_1 = V_2 = V$

$$V_{c1} = V_{c2} = V_c$$

$$i_1 = k_1 [k_2 b(V_s + V_s) + w] [V_s + V_s - V_c]$$

$$i_2 = k_1 [k_2 b(V - V_s) + w] [V - V_s - V_c]$$

$$\begin{aligned} i_1 - i_2 &= k_1 k_2 b(2V_s + 2V_s V - 2V_s V_c) + k_1 w 2V_s \\ &= 2CV_s(2V - V_c)\left(1 + \frac{2w}{k_1 b(4V - 2V_c)}\right) \end{aligned}$$

Hence the formula of the corona current with wind is of the same form as those without wind, the formula of the corona current with wind is that of the corona current without wind multiplied by a factor $1 + \frac{w}{k_1 b(2V - V_c)}$

The number $(2V - V_c)$ is the effective voltage.

Rotor tip speeds are in the order of 150 to 250 meters per second.

The following are examples:

Corona point in still air, 25 kv potential yields $\approx 3\mu A$

Corona point in air, 150 meters per second, 25 kv potential yields $\approx 26\mu A$

Corona point in air, 250 meters per second, 25 kv potential yields $\approx 41\mu A$

Corona points mounted on the rotor tips will therefore have a corona current nine to fourteen times the corona current of the same corona point in still air.

Comparison of corona system alternatives.

In this section we will compare the voltages required, and the complexity of the various corona systems which might be used to solve this problem.

In this comparison we will assume that all the corona points have a diameter of 0.007 cm. and that there are no charged bodies in proximity to the corona points. This assumption is not strictly true in most cases, and the effect of the proximity of charged bodies will influence the effectiveness of the corona point in discharging the ship.

It should be noted that a charging current of 10 microamperes is approximately the maximum current experienced by a helicopter in flight. A charging current of 3 microamperes is a typical charging current for a helicopter in flight. As has been discussed previously, we will assume that the helicopter must be discharged to an energy level of less than one millijoule, which is less than one kilovolt, if the helicopter capacitance is 1000 micro-microfarads. In the discussion which follows, use will be made of Fig. 4 which is drawn from the previously described examples showing the effect of wind velocity on a discharged current.

Fig. 5 shows the extrapolated corona currents for various corona systems. The first system to be used is a single passive corona point in still air. It can be seen from Fig. 5, that this system will result in a ship's voltage larger than 50 kilovolts when the charging current is 10 microamperes. When the charging current is 3 microamperes, the ship's voltage will be larger than 25 kilovolts.

In the second system, let us assume a single passive point into the rotor downwash. Let us assume a downwash velocity of 30 meters per second. We note from the curve that the ship's voltage will be larger than 28 kilovolts when the charging current is 10 microamperes, and will be larger than 15 kilovolts when the charging current is 3 microamperes.

As a third alternative for a passive corona point, let us place the point on the rotor blades. We assume a rotor blade velocity of 200 meters per second, and note that the ship's voltage becomes larger than 11 kilovolts if the charging current is 10 microamperes. For a charging current of 3 microamperes this voltage is 7 kilovolts. Both of these voltages are still far in excess of the maximum safety required for the system.

Now let us consider a single active DC corona point in the rotor downwash (Ref. 8). Assuming again that the downwash velocity is 30 meters per second, we note from the Figure that a discharging current of 10 microamperes will occur when approximately 25 to 30 kilovolts DC is applied to this point. The voltage required to provide a discharge current of 3 microamperes is 16 kilovolts. In this case the final ship's voltage will depend on the sensitivity of the measuring device used to measure the ship's potential and, with a reasonable technique, the latter is easily brought down below the safe value.

It is not worth considering the use of a single active AC corona point in the downwash. The AC voltages required to achieve a safe level of ship's charge will be rather excessive. The AC discharge method, although not requiring a measurement of the ship's potential, is rather inefficient.

Let us now consider an active corona point on the rotor blades. In a typical system, let us assume that we have four active points mounted on the rotor blades for a four-bladed system, one on each blade. We note from Fig. 4 that a 200 meters per second wind velocity will increase the corona current by a factor of about 12. The corona current from a 25 kilovolt square wave applied to the single point, with a wind velocity of 200 meters per second, is of the order of 2.5 microamperes per kilovolt of ship's voltage, as can be seen from Fig. 5.

Fig. 5 is constructed from Fig. 4. We note that the corona current is proportional to wind velocity. For a 25 kilovolt corona point, a wind velocity of 16 meters per second doubles the current. We then see that the effect of the wind velocity on a corona current having a 25 kilovolt point is in the order of a constant times $(1 + \frac{w}{16})$ where w is the wind velocity in meters per second. For a 50 kilovolt point, the equation is a constant times $(1 + \frac{w}{20})$. Thus, in the system under consideration, a discharge current of 10 microamperes is obtained from 4 corona points, with a 25 kilovolt AC voltage, if the ship's voltage is of the order of one kilovolt. This is our safe limit. The ship's voltage will be correspondingly obtained if the discharge current required is 3 microamperes, that is, the ship's voltage will be 300 volts for a 3 microampere charging current. It should be emphasized that these numbers are just an approximation. Since the mobility of the positive and negative ions are not equal, a shift in the zero occurs. For example, in using a 25 kilovolt AC corona discharge system, there will be a zero shift in the order of plus 3 kilovolts, due to this difference in the mobility of positive and negative ions. Thus, unless a bias is used in such a system, the final voltage of the ship will tend toward a value of plus 3 kilovolts with a 25 kilovolt AC cycle per second, and twice this value or 6 kilovolts, with a 50 kilovolt AC corona system.

A DC active corona point on the blades. In this system, we also assume 4 active points mounted on a four-bladed system. However, two points are at a positive potential, and two points at a negative potential. The voltages are the same as for the AC active corona system. With the same

number of corona points this system yields the same current as an AC system. However, the problem of the zero shift, due to the difference in ion mobility, can be handled quite simply by adjusting the positive and negative high voltage potentials.

In the above discussion, we have shown that all the active corona systems in downwash or on the blades, could, theoretically, provide sufficient current to discharge the helicopter to a safe value. All of the passive corona systems described are insufficient to discharge the ship to a safe value. The choice, therefore, of a particular system to be used, depends on certain practical factors, such as the complexity of the system, weight, maintenance and cost. The following discussion will concern itself with these aspects of the corona systems.

In the system using a single active DC corona point in the downwash, the system consists of a probe, a measuring system and a high voltage supply which is powered directly from the ship's power supply. The mounting on a ship is relatively easy. However, the system is quite complex in that a measuring system is required, and that measurement system must be used to control the voltage at that point. The maintenance problem is eased by good accessibility.

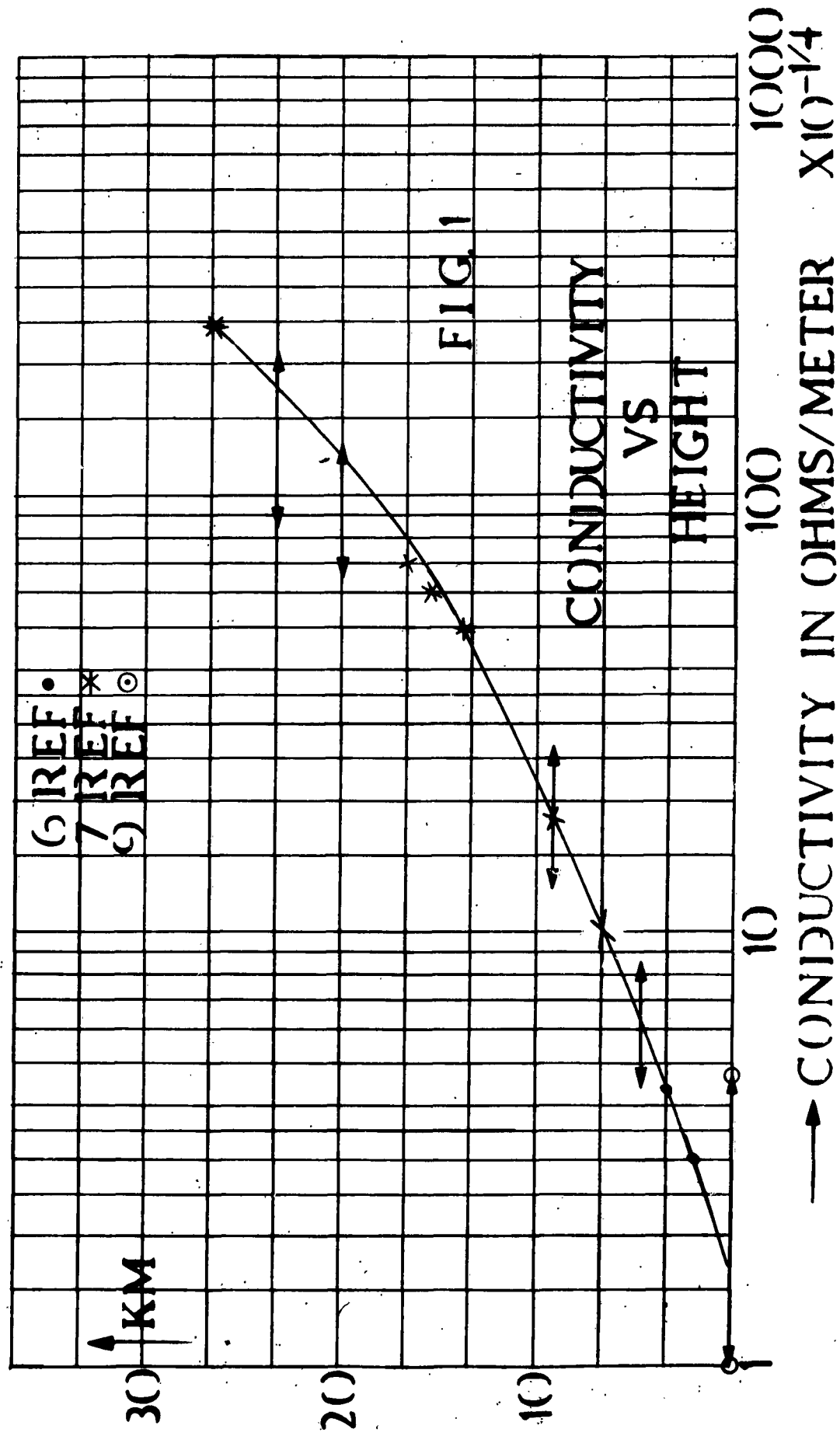
In the active corona systems installed on the blades, the system consists of a number of corona points on the rotors connected to a DC or AC high voltage supply, either in the hub or in the ship. The power is supplied to the system via slip rings or small devices. In these systems the mounting of the equipment is much more difficult, as high voltages have to be transported through the plane system. The accessibility of the high voltage part of the system is not very good.

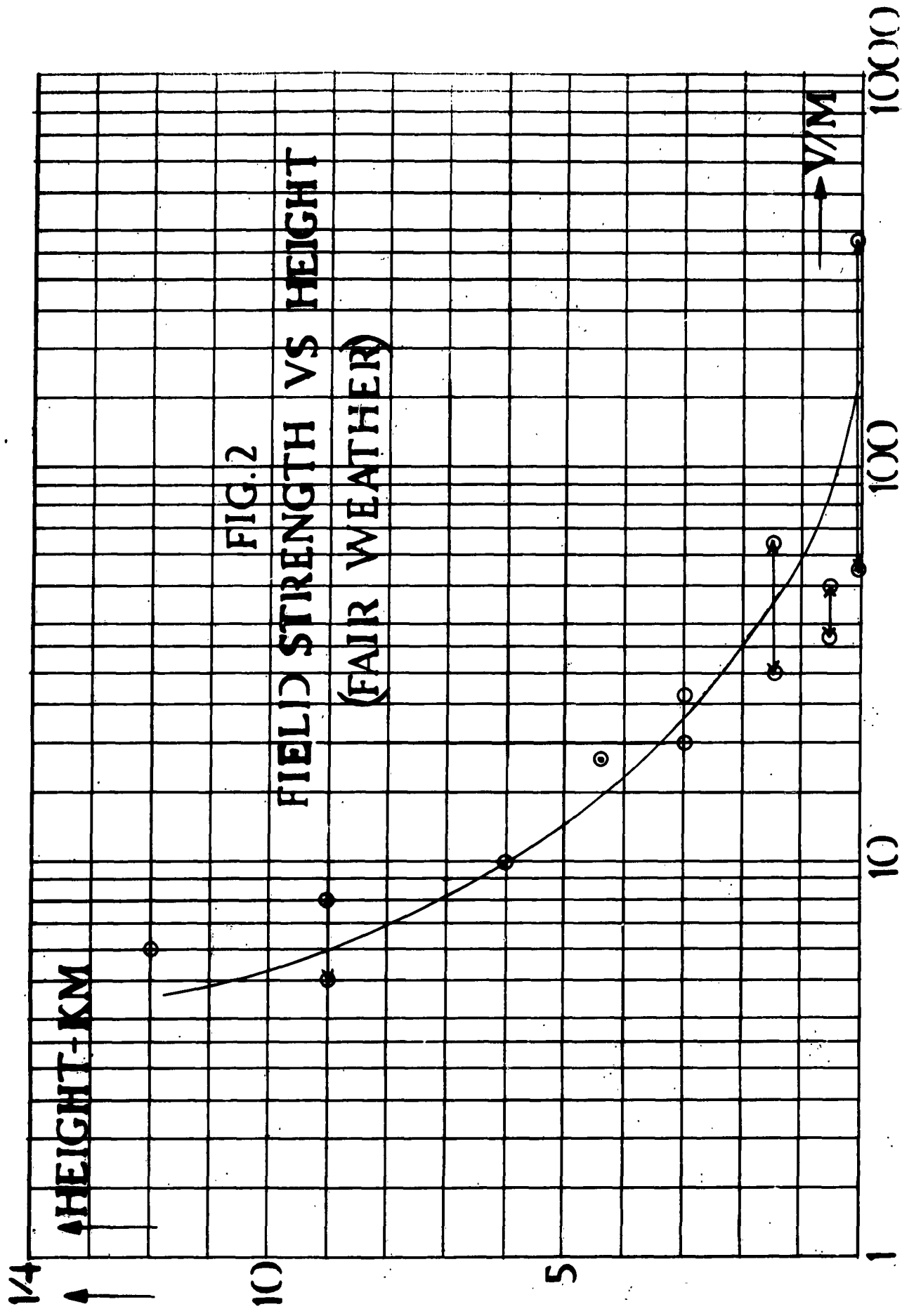
It would be interesting to compare the AC and DC rotor mounted systems. The AC system would have to use low frequencies to minimize the problem of cable shunt capacity as a load on the power supply. A good choice of frequency would be 400 cycles per second, because it is readily available. If a transformer is used to raise the low voltage 400 cycles per second to a high voltage, then the peak voltage which the transformer would have to be of the order of 40 kilovolts, to provide 25 kilovolts rms at the corona point. This means a more difficult transformer design. In the AC system, because of the difference in ion mobility, a bias is necessary to overcome the zero shift. The DC rotor mounted system might use lightweight transistorized high voltage DC supplies. The bias would be provided for in the choice of the positive and negative voltages. Since the power required even at peak discharge is quite small, it is conceivable that a DC discharge system might use storage cells as the primary source of power, which storage cells could be maintained on the rotor system and would have to be exchanged very infrequently.

These considerations seem to make the DC blade corona system with two opposite polarity DC probes, the simplest of the systems described. It should be noted that both these systems, the AC and multiple polarity DC, do not require measurement of the ship's potential, but will automatically reduce the ship's potential in the proper direction.

No discussion of this problem would be complete without considering the most simple solution possible, which is the use of passive discharge devices and an insulated cable system, so that contact with the personnel or load to be lifted is not made via an electrical conductor.

In considering this, we note that the electrical resistance of the cable must be very high, since the electrical resistance will determine the current flow through the load to the ground. Using our previously discussed maximum safe energy dissipation of one millijoule in a human, we can study the situation when the voltage on the helicopter is limited by passive dischargers to 20 kilovolts. If again, we assume that the capacitance of the helicopter is in the order of 1000 microfarads, the stored energy is less than 200 millijoules. To keep the energy in the load to one millijoule requires that the resistivity of the hook and cable be at least 200 times larger than the human or cargo. A typical body resistance of a human is 50 to 150 kilo-ohms. Therefore, the cable resistance must be at least 10 to 30 megaohms. Keeping the cable resistance to this high value under all sorts of conditions of humidity and spray would be quite difficult and quite unreliable.





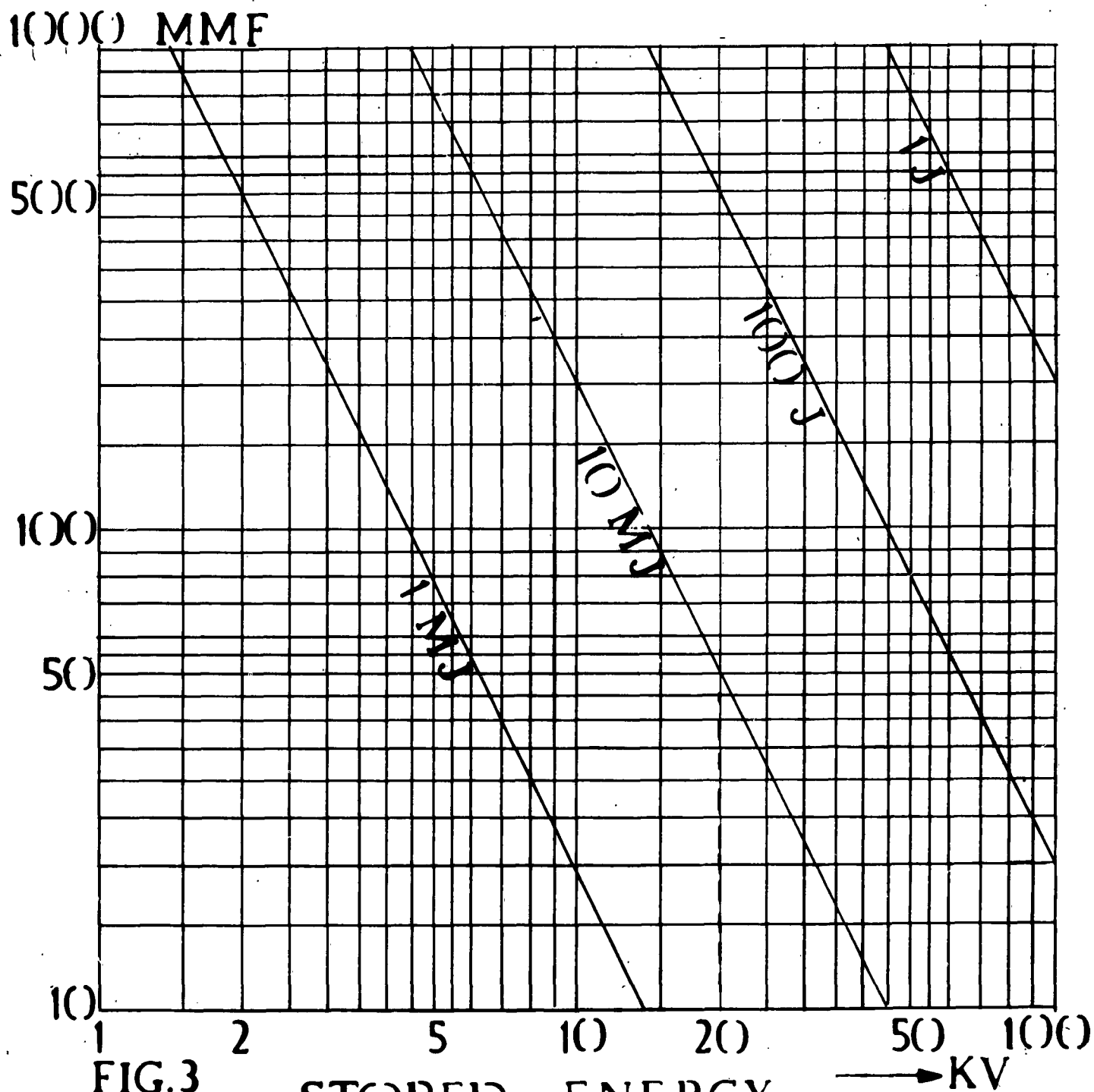
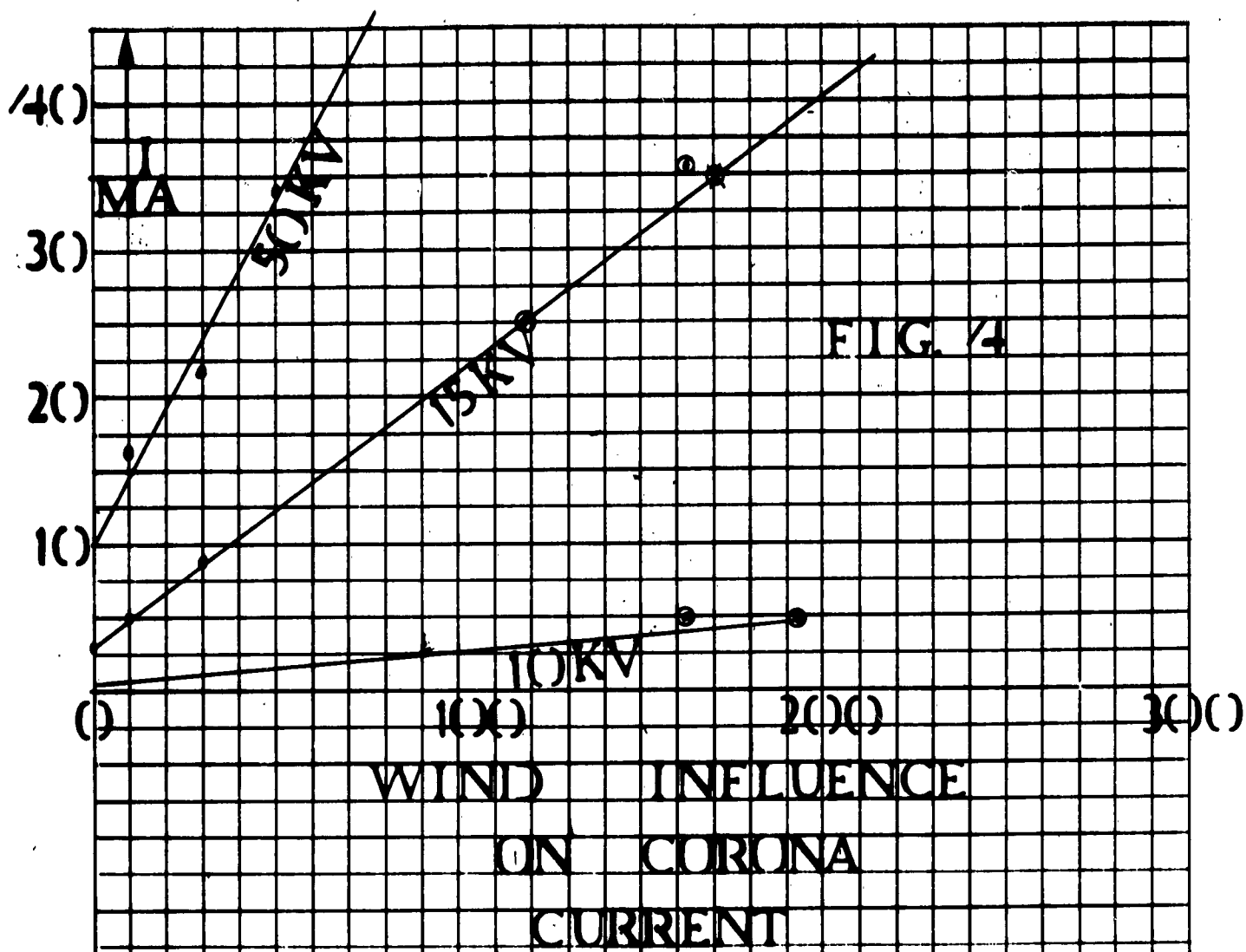
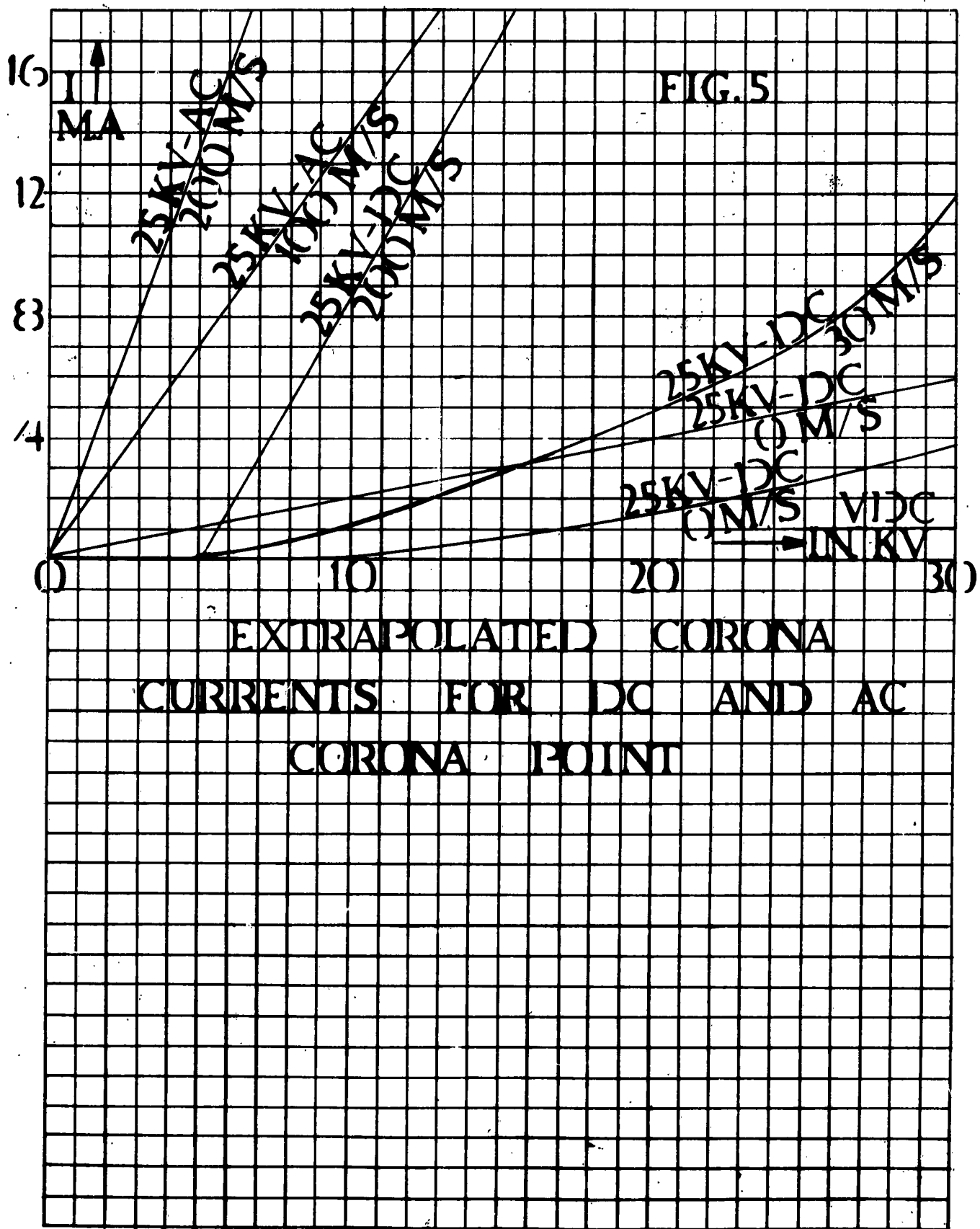


FIG.3

STORED ENERGY
V.S
CAPACITANCE AND VOLTAGE





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The dominant factor in keeping this charge small is a short discharge time constant compared with the charging time constant.

Methods are discussed and evaluated. It is concluded that only corona discharge systems seem to be feasible at this time. Three possible corona discharge methods are discussed.

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